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Modeling concrete like materials under sever dynamic pressures

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ABSTRACT

The behavior of concrete, as well as that of all cohesive-frictional materials, is characterized by a strong dependence on hydrostatic pressure and strain rate sensitivity. The stress–strain response is nonlinear and, depending on the loading path, it can show compaction and dilatancy. Due to its internal constitution, the numerical simulation of this type of materials can be done with a great variety of approaches which are mainly differentiated by the modeling scales and the approximation methods used. Appropriate formulation and calibration of the models are necessary to accurately reproduce the physical phenomena involved in the simulated processes.

A general elastic–viscoplastic model for concrete like materials under high strain rate dynamic loads that produce high confinement pressures, like those present in blast actions, is presented in this paper. The model developed is of phenomenological type and it is formulated within the framework of continuum thermodynamics for irreversible processes with internal variables and small strains. Non-associated plastic flow, cap function and hardening functions that depend on the loading path are proposed. The transition between compaction and dilatancy processes observed in triaxial compression experimental tests can be properly reproduced with the non-associated flow consideration and the proposed hardening functions. The cap function allows the appropriate simulation of the material volumetric response for high confinement pressures. The model formulation is general and it can be used for other cohesive-frictional materials.

The numerical integration algorithm is implemented in a 2D finite element dynamic program that allows solving nonlinear problems of solid mechanics in small strains.

For the model validation, static and dynamic tests with different loading paths and confinement levels for many types of concretes and mortars are analyzed. Numerical results are compared with experimental results obtaining a good description of the main characteristics of this type of materials response under high strain rate pressures.

1. Introduction

The study of the response of structures under severe loading has received more attention during the last decades due to the great number of accidental and intentional explosion events that have taken place all around the world. The structures behavior under blast and impact loads still presents many challenges due not only to the difficulties in the dynamic action determination but also to the need of the characterization of the dynamic response of the materials [1]. Particularly, the study of concrete behavior under this type of actions represents an important feature for the design and analysis of protective structures, nuclear plants, offshore structures, airports and other constructions of massive use.

Generally and specially in the near field, explosive loads produce the collapse of individual structural members that can be caused by the failure of the material itself due to the effects of the blast wave before the structural response can take place [2–6]. The effects of the pressure wave propagation can also have important consequences in the observed failure modes under impact loads [7,8]. After individual components have failed and depending on the magnitude of the local failure, a progressive structural collapse can be developed [9–11].

Because of the impulsive nature of the actions, the material response is different from that under static or low strain rate loads, presenting a sensible strain rate dependency [12–26]. Moreover, the behavior of concrete like materials, even under static loads, is strongly influenced by the confinement levels [27–35].

Computational mechanics allows the simulation of these problems with different types of approaches like finite differences

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method, finite elements method [36–41], mesh free techniques [42,43], discrete elements methods [44–47], and combinations of these techniques. In general the criterion for the use of one approach depends on the specific problem to be solved, the material observation scale and the complexity of the phenomena to be described [48]. In this sense, the use of models on a hydrocode platform can represent an attractive tool for the analysis of problems involving complex loads, geometry and boundary conditions [49–51]. In any case, the results obtained from the numerical simulation strongly depend on the constitutive models used for the materials and their ability to reproduce the involved physical phenomena.

A viscoplastic model for concrete like materials under high strain rate and high pressures is developed in this paper. After a brief description of the main characteristics of this type of materials under impulsive loads and the existent constitutive models, the proposed model is described. Finally, the paper is completed with different validation and application examples.

2. Behavior of concrete like materials under high strain rate severe pressure

When an explosive load is detonated very close or in contact with a structural member, the pressure peak can reach several GPa in a few milliseconds. Intense shock waves can be generated in the material and they can cause material disintegration. On the other hand, if the explosive load is detonated in the air, shock waves typically reach several hundreds of kPa and decay in 10 ms.

Due to its characteristic heterogeneity, the behavior of concrete is markedly nonlinear, even for low static loads. The typical stress–strain behavior under static uniaxial compression for concretes with different strength (see Table 1) is shown in Fig. 1. It is characterized by a softening range produced by the micro-scale cracking.

In the case of multiaxial quasistatic compression tests, three transitions can be observed in the stress–strain curves. The behavior is elastic up to the first transition point that corresponds to the beginning of the stable crack propagation. Then the nonlinear response develops up to the second transition that corresponds to the beginning of the unstable crack propagation that is coincident with the point of minimum volumetric deformation or maximum compaction. Finally, the last transition is that corresponding to the peak load. Depending on the confinement level, important deformations can be reached (in the order of 15% for axial strains and 12% for the case of volumetric strains). Peak stresses and strains increase with the levels of confinement [27].

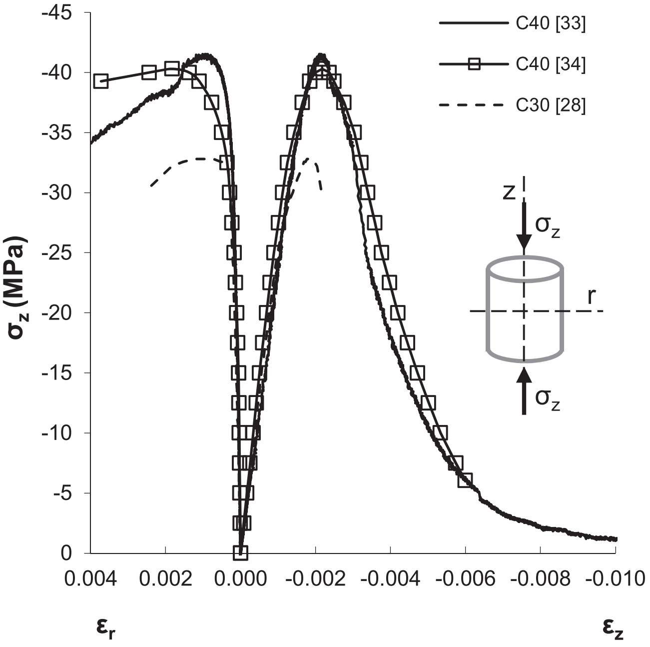

Fig. 1. Uniaxial compression tests.

The post-peak response corresponds to strain localization. The greater deformations are localized in cracks vicinity, while the rest of the element unloads exhibiting a decrease of strains.

Many experimental results for concrete [28–35] and mortar [35,52] under static triaxial compression can be found in the literature. As illustration, the results obtained by Vu et al. [33] for C40 concrete are presented in Fig. 2. The results presented by Sfer et al. [28] and Lu et al. [29], like most of the available experimental results, correspond to moderate confinement levels (up to 60 MPa), while experimental results corresponding to high confinement pressures (in the order of 600 MPa) can be found in the papers by Gabet et al. [32], Vu et al. [33] and Poinard et al. [34]. All these authors have observed that dry concrete reaches a limit state characterized by a transition from compaction to dilatancy. This transition can occur for the peak load in the case of low to moderate confinement or during the increment of the axial load in the case of high confinement levels. This behavior is depicted in Fig. 3 where the volumetric response obtained in Vu tests [33] is presented.

Table 1
Materials properties of concrete and mortar.

Material	Concrete								Mortar	
Identification	C40	C40	C55	C40	C70	C21	C30	C70	M45	M46
[Ref]	[33]	[34]	[85]	[86]	[25,88]	[87]	[28]	[89]	[35]	[12]
Young modulus, E (MPa)	24,000	26,000	31,000	20,000	39,480	19,580	26,600	30,000	20,000	20,000
Poisson ratio, ν	0.13	0.21	0.21	0.2	0.2	0.20	0.20	0.2	0.20	0.2
Quasistatic compression strength, f_{c0} (MPa)	41.54	40.3	56	39.3	70	22.06	32.8	70	45	46
Quasistatic compression elastic limit, f_y (MPa)	32	32	50	32	50	15	24	50	30	34
Compression/tension elastic limit ratio [38], R_0	10	10	10	10	20	10	10	10	10	10
Biaxial/uniaxial compression strength ratio [38], R_{bc}	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16
κ^{vp} value for the quasistatic peak compression stress [38]	0.12	0.12	0.12	0.12	0.12	0.15	0.17	0.12	0.12	0.12
Ratio of octahedral ratios [38], γ	2.2	2.2	2.2	2.2	2.1	2.2	2	2.2	2.1	2.2
Point of confined compression yielding curve [38], p_h (MPa)	650	650	650	650	1000	13.79	60	1000	650	650
σ_{cu} (MPa)	1600	1600	1600	1600	1450	80	195	1450	1600	1600
Quasistatic tension strength, f_{t0} (MPa)	4.15	4.0	5.0	6.9	3.5	2.76	2.5	7.0	4.5	3.4
Quasistatic crushing energy, G_{c0} (MPa m)	1.2E-02	1.2E-02	1.6E-02	1.6E-02	1.2E-02	6.0E-02	1.2E-02	1.2E-02	1.0E-02	1.0E-02
Quasistatic fracture energy, G_{f0} (MPa m)	1.2E-04	1.2E-04	1.6E-04	1.6E-04	1.2E-04	3.5E-05	1.2E-04	1.2E-04	1.2E-04	1.2E-04